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LEACHING OF PLANT NUTRIENTS AND TOTAL PHENOLIC SUBSTANCES FROM SOME FOLIAGE LITTERS - A LABORATORY STUDY

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LEACHING OF PLANT NUTRIENTS AND TOTAL PHENOLIC SUBSTANCES FROM SOME FOLIAGE LITTERS - A LABORATORY STUDY

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Abstract

Leaf litter from eight tree species (*Fraxinus excelsior*, *Acer platanoides*, *Alnus glutinosa*, *Populus tremula*, *Sorbus aucuparia*, *Betula pubescens*, *Salix caprea*, and *Pinus silvestris*) were exposed to 13 consecutive leachings with water. After 10 leachings a freeze-thaw cycle was introduced. Each leachate was analyzed for pH, total phenolic content and the total amount of the nutrients N, P, K, Ca, Mg and Mn. In a separate study the weight loss on repeated leachings was investigated.

The leaching properties for plant nutrients of various litter types were in good agreement with those for organic matter. In broad-leaf litter 70-90% of the potentially leachable fraction could be leached in comparison with only about 10% from the needle litter. Phenolic substances amounted to 0.5-4.0 % of the totally leached substances.

The average leachability, defined as the fraction of the total contents of a certain element lost from the litter after 10 consecutive leachings, decreased in the order: K > Mg > P > Mn > N > Ca. Potassium, magnesium and phosphorus were rapidly leached from all broad-leaf litters. Between 50 and 100% of the total contents of these elements were generally removed during 13 leachings, the major part during the first leaching. The effect of a freeze-thaw cycle was small, although somewhat more pronounced for birch leaf litter than for the other broad-leaf litter types.

Calcium and nitrogen were leached only to a minor degree from all litter types, while the leachability of manganese was intermediate. With needle litter, though, the leaching was small for all nutrients, but it was significantly enhanced by freezing and thawing. Needles from fertilized Scots pine differed from non-fertilized ones only as regards a larger leaching of potassium.

It was concluded that structural properties of the litters as well as concentration of the element and the chemical forms in which it occurs were responsible for the varying leaching patterns of nutrients and litter types.

1. INTRODUCTION

Water-soluble substances, released from litter by leaching are capable of influencing forest soils in several ways. Besides decomposition, leaching is a major process, determining the rate and timing of nutrient recycling to plants. Leached organic compounds may further serve as an easily available energy source increasing the microbial activity of underlying soil (Witkamp 1966), while, on the other hand, water-soluble tannins and polyphenolic substances are thought to inhibit microbial activity (Davies *et al*. 1964a, b; Lewis and Starkey 1968, Harrison 1971, McClaugherty 1983)). Chelating litter substances of polyphenolic nature are further considered to play an important part in podzolization by solubilizing sesquioxides (Bloomfield 1953, 1954, 1965, Coulson *et al*. 1960, Davies 1971). Both quantity and quality of leached substances are thus of interest when assessing their role in the forest ecosystem.

Nykvist (1963) found that both amount and character of leached substances differed strongly with the litter type. Considerable amounts could be washed out from most broad-leaf litter types, while needle litter appeared hardly to leach at all. He also noted (Nykvist, op.cit.) that repeated leachings, and mechanical disruption of the litter, increased the leaching losses of both organic and inorganic constituents. This, together with the fact that the proportion of the water-soluble substances that could be leached instantly differed markedly with the type of the litter, indicates the great influence of structural features on the process.

Plant nutrients like K, Na, and Mg, which are not structurally bound or only partly so, are often quickly leached from litter (Kucera 1959, Brinson 1977, Edmonds 1980, Staaf 1980), while nitrogen and calcium, for example, are much more difficult to leach from leaf litter (Gosz *et al*.1975).

This paper reports on a laboratory study on leaching from leaf litter of eight tree species. The selected litter types are suggested to be representative of habitats of different nutrient status and successional aspects occurring in Swedish forests. The following aims could be identified:

- to investigate the loss of selected organic and inorganic constituents from different litter types at repeated leachings.

- to investigate the effect of freezing/thawing on the loss of the same constitutents from leached litter.

- to see if ultrasonic treatment may serve as a method for determining the potentially leachable amount of nutrients in litter.

2. MATERIALS AND METHODS

2.1. Litter collection

The litter samples were taken from trees at leaf abscission in the autumn of 1979. Two sites of contrasting appearance were chosen for the collections, namely one mixed deciduous forest near Uppsala on fertile calcareous clay soil and one forest on a sandy nutrient-poor Scots pine heath, Ivantjärnsheden, in central Sweden. Leaf litter from the following tree species were used:

Species	Habitat	Locality
Fraxinus excelsior (ash)	mixed deciduous forest	Uppsala
Acer platanoides (Norway maple)	"	"
Alnus glutinosa (black alder)	river bank	"
Sorbus aucuparia (mountain ash)	small brook ravine[2]	Ivantjärnsheden
Populus tremula (aspen)	"	"
Betula pubescens (white birch)	young pine stand	"
Salix caprea (sallow)	small brook ravine[2]	"
Pinus silvestris (Scots pine)	young pine stand	"
Pinus silvestris " "	Ih II, fertilized pine stand[1)]	"

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1) continuous fertilization since 1974 (Aronsson et al. 1977)

2) close to the young pine stand

2.2 Leaching procedure

After air-drying at room temperature for two weeks, one sample of each litter type, corresponding to 10.0 g dry weight (85°C), was leached in demineralized water. The leaves were kept intact or broken into large pieces when necessary. The samples were put into 1000 ml Erlenmeyer flasks and 200 ml demineralized water added, whereafter the flasks were incubated on a rotary shaker at 24°C for 2 hours. After incubation the samples were sucked dry on ash-free filter paper and immediately thereafter incubated with a new portion of water. Each litter type was exposed to ten such repeated leachings. After that the samples were frozen at -20°C, thawed, and leached three more times. All filtrates were kept frozen until further analytical treatment.

2.3 Chemical analyses

Original non-leached litter samples were milled in a laboratory mill with a screen allowing particles less than 1 mm to pass. The amounts of water-soluble and ethanol-soluble substances were determined by ultrasonic treatment of the milled samples for three times in an ultrasonic bath and weighing the samples after filtration and drying. Analysis for sulfuric-acid lignin in the samples was carried out according to Bethge *et al*. (1971) (see also Berg *et al*. 1982).

The milled samples of non-leached material were also analyzed for their total contents of N, P, K, Ca, Mg and Mn. The analyses were made in duplicate. Nitrogen was determined by a semi-micro Kjeldahl procedure (Nihlgård 1972). After a wet oxidation in HNO_3+$HClO_4$, analyses were performed for P by the molybdenum-blue method as modified by John (1970) and for K by flame photometry. Calcium, Mg, and Mn were determined by atomic absorption spectrophotometry, the first-mentioned element in 1% LaCl-solution.

The extracts were analysed in the following way:

- pH was measured electrometrically.
- polyphenolic and phenolic substances were determined in the extracts by the method of Lowry *et al*. (1951) using phenol as a standard.

From each filtrate one aliquot of 25 ml was evaporated to almost dryness and analyzed for nitrogen with an ammonium-sensitive electrode (Orion 95-19) after oxidation in 1 ml conc. H_2SO_4 with K_2SO_4+$CuSO_4$ as a catalyst followed by a dilution to 100 ml. Another aliquot of 50 ml was evaporated to almost dryness, the residue oxidized in 5 ml HNO_3+$HClO_4$, excess acid evaporated, diluted to 100 ml with demineralized water and analyzed for P, K, Ca, Mg and Mn as described above.

3. RESULTS

3.1 Initial chemical composition

The investigated litters exerted a broad spectrum of chemical composition (Table 1). Broad-leaf litter types had fairly high levels of water-soluble substances, ranging from 25% to 35% of total weight and low levels of ethanol-solubles (2-5%). Needle litter of pine had much lower contents of water-solubles but, on the other hand, rather high levels (10-11%) of ethanol soluble substances.

The lignin levels varied from 16% to 29%. A group of high-lignin litters might be identified, consisting of birch, pine and sallow. These are all litter types collected on low-fertile sites, and there was a tendency, although only a weak one, for tree species associated with eutrophic soils, like alder and ash, to have the lower values.

All broad-leaf litters were comparatively richer in nutrients than the needle litter (Table 1). This applied to most elements, with the exception of manganese. Of the broad-leaf litters, alder and maple were exceptional with high nitrogen and phosphorus contents, respectively.

3.2 Weight loss during leachings

The method utilized did not allow total dry weight loss of the litters to be determined until after all 13 leachings. From Table 2 it is seen that for birch 62% of the initial water-soluble substances were leached during this procedure, and for the other broad-leaf litters the figure was slightly higher, or around 75-90%. For pine needle litter this proportion was much lower, although there was a big difference between needles from fertilized and unfertilized trees, those from fertilized trees being the ones most liable to leach nutrients. The figures on the size of the pool of water-soluble substances are slightly higher than those presented by Nykvist (1963) for the same litter types, a fact which might be due to the somewhat differing analytical techniques. The ultrasonic treatment used by us probably gives a more complete leaching of the soluble compounds.

In a separate study with only four litter types the weight loss was investigated after each separate leaching (Figure 1). Sallow and mountain ash leaves lost about 30% of their weight already after 4-5 leachings, after which the weight loss quickly levelled off. Birch leaves showed steadily increased weight losses with successive leachings up to a maximum of about 20%. Pine needles showed a similar pattern, but the total weight loss only amounted to 3-4% of the initial weight. The difference between the needle litter types was smaller than in the original study. There did not appear to be any significant influence of the freeze-thawing cycle after the 10th leaching for any litter type.

3.3 Leaching of plant nutrients

3.3.1 Basic results

Fraxinus excelsior (ash)

The results for this litter type are presented in Figure 2a and Table 3a. The sequency for relative nutrient losses for the first 10 leachings was: Mg > P > K > Ca > Mn > N. Ash litter was the most readily leached of the investigated litters. Elements like magnesium and phosphorus were more or less completely removed from the leaves. Some values even exceeded 100%, which must be contributed to the summation of analytical errors and contaminations during repeated leachings. The leaves contained extremely little manganese, and the values for this element are therefore rather uncertain. Nutrient losses decreased smoothly with successive leachings, and for all elements the first leaching washed out about as much as all the following ones. Freezing hardly affected the leaching at all. The ultrasonic treatment generally gave somewhat lower values than 13 consecutive leachings but for nitrogen and potassium they were higher.

Acer platanoides (Norway maple)

The results for this litter type are presented in Figure 2b and Table 3b. The sequence for relative nutrient losses for the first 10 leachings was: K > P > Mg > Mn > N > Ca. Maple leaf litter also belonged to the easily leached litters, but less so than ash leaves. One clear difference from the ash litter was the comparatively low calcium loss. One freeze-thaw cycle gave low to moderate rises in the ongoing leachings. Also for this litter the first leaching was much more efficient than the following ones.

The amounts of nutrients lost after ultrasonic treatment were in fairly good agreement with the total loss after 13 leachings. For nitrogen and potassium the ultrasonic treatment was considerably less efficient, though.

Alnus glutinosa (black alder)

The results for this litter type are presented in Figure 2c and Table 3c. The sequence for relative nutrient losses for the first 10 leachings was: K > P > Mg > Mn > Ca > N. In most respects leaching of the alder leaves was similar to that of the maple leaves. The low leachability of nitrogen was noteworthy in spite of the very high nitrogen concentration. Freezing and thawing had little influence on the leaching of elements in this litter type.

Sorbus aucuparia (mountain ash)

The results for this litter type are presented in Figure 2d and Table 3d. The sequence for relative nutrient losses for the first 10 leachings was: K > P > Mg > N > Mn > Ca. This litter showed a very similar leaching pattern to alder and maple, with the exception of the relatively high nitrogen loss. The leaching after ultrasonic treatment was lower than that obtained after the 13 leachings in the case of nitrogen and phosphorus, but otherwise they gave rather consistent results.

Populus tremula (aspen)

The results for this litter type are presented in Figure 2e and Table 3e. The sequence for relative nutrient losses for the first 10 leachings was: K > Mg > Mn > Ca > P > N. This litter differed from the foregoing ones in two respects: a) a low leaching rate of phosphorus and b) a significant effect of freeze-thawing on nitrogen leaching.

The low leaching loss of phosphorus is not explained by low concentration in this litter type. The initial concentration was, in fact, considerably lower for alder and mountain ash, which both had considerably higher leaching rates of phosphorus. As for the relatively high calcium loss from this litter, it had the second highest concentration of this element among the litter types. The ultrasonic treatment gave higher values for phosphorus and potassium in relation to total losses during the 13 leachings.

Betula pubescens (white birch)

The results for this litter type are presented in Figure 2f and Table 3f. The sequence for relative nutrient losses for the first 10 leachings was: K > Mg > P > Mn > Ca > N. In comparison with the other broad-leaf litters, birch leaves had about the same relative loss rate of potassium, somewhat lower for nitrogen and phosphorus and much lower for the rest of the elements. To this was coupled a less distinct reduction in loss rate with successive leachings and a more marked effect of the freeze-thaw cycle. The nutrient concentrations of birch leaves did not differ particularly from other broad-leaf litters used in this investigation.

Salix caprea (sallow)

The results for this litter type are presented in Figure 2g and Table 3g. The sequence for relative nutrient losses for the first 10 leachings was: K > Mg > Mn > Ca > P > N. This litter leached comparatively little phosphorus, but otherwise the pattern was very similar to that of the other broad-leaf litters. The leaching following ultrasonic treatment differed on several points from that during the 13 leachings. Much less nitrogen but more phosphorus, calcium and magnesium was released.

Pinus silvestris (Scots pine): unfertilized

The results for this litter type are presented in Figure 2h and Table 3h. The sequence for relative nutrient losses for the first 10 leachings was: N > K > P > Mg > Ca > Mn. The results differ considerably from those of broad-leaf litters by:

a) much lower leaching rates for all elements, except for nitrogen.
b) only small differences in leachability among the elements.
c) the loss pattern over successive leachings was much more irregular.
d) a freeze-thaw cycle had a drastic effect on leaching of most elements.
e) the ultrasonic treatment gave a much higher release in comparison to 13 leachings, except for nitrogen.

Pinus silvestris (Scots pine): fertilized

The results for this litter type are presented in Figure 2i and Table 3i. The sequence for relative nutrient losses for the first 10 leachings was: K > N = Mg > P = Mn > Ca. In principle this litter exposed the same pattern as the needles from unfertilized trees. The absolute and relative losses of nitrogen and potassium were much higher, though. The concentration of nitrogen was also higher in needles from fertilized trees, but not of potassium.

3.3.2 Influence of litter type

The results for each litter type are summarized in Figure 3 and Table 3. In the present context "leachability" is defined as the fraction (in per cent) of the original content that is leached in 10 consecutive leachings. Then, by adding these percentages for the six studied nutrients for a certain litter we obtain a "leachability index" for this litter type. This index ranks them as follows: Fraxinus (434), Populus (353), Sorbus (291), Alnus (287) Salix (284) Acer (282), Birch (185), Pinus; fertilized (66) and Pinus; unfertilized (36). From this it is obvious that pine needles have a much lower leachability than any of the broad-leaf litters. On the other hand, their leaching was relatively much more affected by freezing the litter. Of the broad-leaf litters, birch leaves had a notably low leachability figure and ash leaves an exceptionally high one.

The most obvious influence of litter type on the leachability of different elements was found for nitrogen. Here pine needle litter differed from broad-leaf litters by its relatively higher losses. For most broad-leaf litters nitrogen was the element with the lowest leachability.

3.3.3 Differences between nutrients

By ranking the elements by leachability from 1 to 6 for each litter type and summing up the obtained figures for a certain element for all nine litter types we get an index on their relative leaching tendency. The following gross ranking was obtained in this way: K > Mg > P > Mn > N > Ca. The mean leachability for K was 77 per cent and for Ca it was 24 per cent, but as already mentioned there were great variations among litter types both in magnitude and rank among nutrients.

3.3.4 Influence of nutrient concentration

The regression analysis presented in Table 4 indicates that on average litters tended to leach more of a certain element the higher the initial concentration of this element. This pattern was most well-developped for potassium and phosphorus, where 80-90% of the variability could be explained by the concentration factor. Noteworthy exceptions from the general rule were magnesium (broad-leaf litters), nitrogen and manganese. For both the latter elements it appears that the pine needle litters caused this divergence, since deleting these litters from the material improved the relationship and made it reach the $p<0.05$ significance level.

Only calcium exhibited clearly higher leachability with increased element concentration. There were positive correlation figures for most elements, but they did not exceed the significance level of $p<0.05$.

3.4 Leaching of phenolic substances

Maple leaves was the litter type which leached most phenolic substances, in all 13.8 mg g^{-1} dw, followed by alder with 5.0 mg g^{-1} dw (Table 5). Pine needles released much lower amounts than any of the broad-leaf litters. For those litters which leached the largest amounts of phenolics, the release was very highly concentrated to the first leaching event, while litters with lower losses had a more evenly distributed release over the leachings. Hardly any phenolics were released from pine needles until after the freeze/-/thaw treatment.

The analytical procedure utilized by us allows only relative comparisons of leached amounts from different litter types to be made and the absolute values must be regarded as approximations. Their accuracy will depend on the degree of condensation and molecular weight of the leached phenolic or polyphenolic substances.

3.5 pH of leachates

There was a general tendency towards increased pH with successive leachings (Figure 4). The increase over all leachings was of a magnitude of 0.5-1.0 units of pH. Another observation was a drop in pH for one or two leaching events following the freezing - thawing of the litter. Pine needle litter exhibited much more irregular patterns than the broad-leaf litters; no obvious trend in pH development could be seen for this litter.

4. DISCUSSION

When soaked in water all the investigated leaf litters leached both organic and inorganic constituents, but to quite a varying extent. The broad-leaf litters initially contained between 15 and 30% water-soluble substances in their tissues, and for most litters 80-90% of this substance could be leached by 13 consecutive leachings. Birch leaves differed a bit from the other broad-leaf litters by having a lower amount of water-solubles as well as a lower leachability, but not as low as pine needles. The different degrees of organic matter leachability as compared to the potentially leachable fraction indicates an influence on the leaching process by structural properties of the litter as pointed out by Nykvist (1963). Nykvist also found, as we did, that broad-leaf litters generally were exposed to a rapid weight loss caused by leaching, while for needle litter it was very slow. In our study, birch leaves had an intermediate position with respect to leaching rate of organic matter.

Of the organic constituents in the leachates only gross phenolic substances were identified. In the presently investigated litters these components amounted to only a few percent of the leached organic matter. The differences in leaching rates of plant nutrients among litters appears to be similar to those of organic matter. Phenolic compounds could be leached in the largest amounts from maple litter; an amount corresponding to about 4% of total dry weight was lost during 13 consecutive leachings. The corresponding figures for the other litter types fell in the range 0.5-2.%. The presently used analysis identifies phenolic groups, but it gives no information on the nature of the substances. Soluble polyphenols, notably tannins, have been proposed to act as mobilizing agents on iron and aluminium in the podzolization process (Coulson et al. 1960, Bloomfield 1965, Davies 1971). However, King & Bloomfield (1968) found no clear relation between the mobilizing action of extracts from various litter types and their total concentrations of polyphenolic substances. The complexing ability of tannins, which has been suggested to stabilize proteins in litter, thus making them less susceptible to decomposition (Handley 1954, 1961; Davies et al. 1964a; Basaraba & Starkey 1966), varies considerably with type of tannin, degree of condensation and external conditions like pH (Davies et al. 1964a, Lewis & Starkey 1968). Thus, it appears difficult to draw any reliable conclusions from our data on the pedogenetic importance of various litter types with respect to water-soluble polyphenols.

The leaching of plant nutrients was generally well correlated with the initial concentration of the respective element in litter. However, besides concentration, the litter structure appears to be of importance for the leaching rate. Thus, needle litter showed both much lower leachability and a slower leaching of most elements than the other litter types, probably becuase of its thick cuticule and general xeromorphic character. Nitrogen fertilization may have induced some structural change in the needle litter, as indicated by a considerably higher leachability of potassium from needles of fertilized than of unfertilized trees. No such effect was noted for the other elements. For birch leaves the leachability of most elements was lower than for the other broad-leaf litters, potassium being a notable exception. From our observations it appears that potassium can be almost completely leached from all litters unless extremely impermeable to water, while the leaching of other, less easily mobilized, nutrients is more sensitive to minor differences in structural properties of the "soft" litter types.

For the litters with low leachability it is clear that the break-up of the litter structure by freezing has a significant influence on the subsequent nutrient leaching. Since most of the broad-leaf litters had already lost large amounts of nutrients after 10 leachings the effect of a freeze-thaw treatment was relatively small for these litter types. There was a certain tendency, though, for the effect to be more developed for the structural elements nitrogen and calcium. If the litters had been frozen and thawed earlier in the leaching sequence the effect might have been greater, but since almost all of the potentially leachable elements of the "soft" broad-leaf litters were lost during the first few leachings the effect would have been marginal for these litters anyway. In nature, thus, freezing and thawing probably only has significance in speeding up nutrient cycling in ecosystems dominated by needle litter or other "tight" litter types. In the Scandinavian climate, freeze-thaw cycles in the litter layer are typical of autumn and spring seasons. The frequency of such events during one year is exemplified below by measurements in a pine forest and a clear-cut area at Ivantjärnsheden in central Sweden. The temperature was measured at 3 cm depth in the humus layer during the period 781001-791001.

	Number of events	
Temperature interval	Old forest	Clear-cut
>+1 C <-1 C >+1 C	1	2
> 0 C < 0 C > 0 C	7	46

There was a great variation in leachability among the studied nutrients, reflecting different chemical and physical bonds in the plant tissue. Potassium, magnesium and phosphorus, which form a group of highly leachable elements in the investigated litters, needle litter excepted, are all mobile elements that are incorporated only partly in organic components (Tukey 1970, Mengel & Kirkby 1982). Olsen (1948 a, 1948 b) found that in beech leaves the proportions of the total element content occurring in the cell sap increased strongly during senescence; for potassium to almost 100% and for the other two elements to 80-90 %. Potassium, which exists in ionic form, could then be leached almost completely, if not prevented by physical and anatomical litter properties. Magnesium and phosphorus to a somewhat greater extent occur either adsorbed or in metal-organic complexes in litter (Mattsson & Koutler-Andersson 1946, Fries 1952), which explains their lower leachability. Especially for phosphorus the differences in leachability among litter types were great. These differences were largely related to the concentration of phosphorus, in that litters with an initial concentration higher than 1 mg g^{-1} had a high leachability and those below this level a low one. Phosphorus is known to be withdrawn from senescing leaves of deciduous trees (Tamm 1951, Guha & Mitchell 1966, Woodwell 1974) and it is possible that the various values for leachability may be inversely related to the tranlocation intensity of the litter type. An efficient back-translocation to twigs and branches would reduce both total concentration and the soluble fraction, leaving little phosphorus in leachable form in the litter. Fries (1952), who investigated several deciduous tree leaves, found an especially low translocation at senescence in ash leaves, and in the present study this litter type was also the one having the highest leachability for phosphorus.

Nitrogen was leached only to a low degree, irrespective of its concentration in litter. Not even from alder litter could any large amounts be leached in spite of its exceptionally high nitrogen concentration. This fact was also noted by e.g. Viro (1955). Low levels of both organic and inorganic nitrogen forms may account for the low leachability. Thus Olsen (1948 a), for example, noted that although about 50 % of the total amount of nitrogen was translocated from beech leaves at senescence the fraction appearing in the cell sap of leaves never exceeded 10 %, a much lower fraction than he observed with phosphorus or magnesium.

Calcium is normally considered to be an immobile element (Tukey 1970), which was confirmed by the low leaching figures for this nutrient in the present study. Much of the calcium is bound tightly to cell wall structures, but since the leachability was positively correlated with concentration the litters with high calcium concentration probably had a higher percentage of non-bound calcium. In many plants calcium is precipitated as oxalate, and Viro (1955) assumed that the low leachability of calcium from needle litter could be explained by this. On the other hand, this study shows that calcium, relatively seen, is leached less readily from needle litter than any other element. It might well be that with needle litter the structural properties override any effect of chemical bonds on element leaching. It should be noted that Viro (op. cit.) worked with milled litter thereby eliminating structural differences.

The leachability of manganese was intermediate between the extremes discussed above. The function and appearance of manganese in plants is similar to that of magnesium, but the former element is a bit more immobile (Wittwer & Teubner 1959). As expected there was a good agreement between the leachability of these two elements, that of magnesium being consistently higher. Variations among litter types were largely consistent with the general leachability pattern.

One aim of this study was to evaluate the possibility of using ultrasonic treatment as a means of determining the potentially leachable fraction of various nutrient elements. Irrespective of whether we define this fraction as the element loss after 10 or 13 leachings, no good correspondence between the ultrasonic treatment and leaching was found. For needle litter the ultrasonic treatment gave much higher values than repeated leachings. With broad-leaf litters the situation is more unclear; both over- and underestimates occurred frequently. For nitrogen there was always considerable disagreement between the methods, but for the more readily leached elements, like potassium and magnesium, the discrepancies appeared to be smaller. The conclusions, though, must be that ultrasonic treatment does not seem to be very useful in defining a leachable plant nutrient fraction in plant litter.

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Table 1. Main chemical composition of the investigated forest leaf litter types.

	Water solubles (%)	Ethanol solubles (%)	Sulfuric-acid lignin (%)	Ash (%)	N	P	K	Ca	Mg	Mn
							(mg g^{-1})			
Fraxinus excelsior	26.4	1.9	16.0 (22.3)[1]	12.2	8.63	1.96	15.3	33.2	2.28	0.03
Acer platanoides	35.0	3.0	17.4 (28.1)[1]	11.9	5.07	3.15	13.1	20.4	1.46	0.12
Alnus glutinosa	28.1	4.7	17.3 (25.7)[1]	8.0	21.0	0.56	3.90	27.9	3.33	0.67
Sorbus aucuparia	26.9	5.1	18.4 (27.1)[1]	5.5	7.12	0.31	10.8	12.4	2.86	0.30
Populus tremula	27.7	2.6	19.9 (28.6)[1]	9.3	8.15	0.93	5.09	29.9	4.69	0.53
Betula pubescens	26.3	3.3	29.0 (41.2)[1]	5.7	9.11	1.38	7.82	14.6	3.95	3.36
Salix caprea	31.4	1.9	23.3 (34.9)[1]	8.4	9.41	0.49	11.9	28.5	3.37	0.12
Pinus silvestris	13.7	11.4	24.3 (32.4)[1]	2.3	3.61	0.27	0.95	7.50	0.35	1.74
Pinus silvestris (fert)	14.5	10.2	24.0 (32.0)[1]	2.0	4.85	0.19	0.98	4.90	0.59	1.01

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[1] as calculated from the non-soluble substances.

Table 2. Total weight loss from the investigated litters after 13 consecutive leachings as compared to the initial amount of water-soluble substances.

Litter type	Initial concentration of water-soluble substance (%)	Leaching of dry matter % of dry weight	 % of initial water-solubles
Fraxinus excelsior	26.4	22.3	84
Acer platanoides	35.0	29.4	84
Alnus glutinosa	28.1	21.3	76
Sorbus aucuparia	26.9	22.8	85
Populus tremula	27.7	25.2	91
Betula pubescens	26.3	16.3	62
Salix caprea	31.4	27.9	89
Pinus silvestris (unfertilized)	13.7	1.3	9
Pinus silvestris (fertilized)	14.5	6.3	43

Table 3a. Initial amounts of plant nutrients in leaf litter of Fraxinus excelsior and the loss of these nutrients at leaching. Figures are given both as relative amounts (%) and as absolute amounts ($mg\ g^{-1}$) lost from 1000 mg dry weight of litter. All leachings were made at 24°C.

		N	P	K	Ca	Mg	Mn
Initial amount ($mg \cdot g^{-1}$)		8.63	1.96	15.3	33.2	2.28	0.030
Amount lost during							
- leachings 1-10	($mg\ g^{-1}$)	1.49	2.02	11.4	24.2	2.49	0.017
	(%)	17	103	75	73	109	57
- leachings 11-13[1)]	($mg\ g^{-1}$)	0.07	0.13	0.1	0.3	0.05	0.000
	(%)	1	7	0	1	2	0
- leachings 1-13	($mg\ g^{-1}$)	1.56	2.15	11.5	24.5	2.54	0.017
	(%)	18	110	75	74	111	57
Amount extracted by ultrasonic treatment	($mg\ g^{-1}$)	3.70	1.27	14.5	21.6	2.10	0.021
	(%)	43	65	95	65	92	70

1) One freeze/thaw treatment was made between leaching 10 and 11.

Table 3b. Initial amounts of plant nutrients in leaf litter of Acer platanoides and the loss of these nutrients at leachings. Figures are given both as relative amounts (%) and absolute amounts (mg g^{-1}) lost from 1000 mg dry weight of litter. All leachings were made at 24^{o}C.

		N	P	K	Ca	Mg	Mn
Initial amount (mg·g^{-1})		5.07	3.15	13.1	20.4	1.46	0.120
Amount lost during:							
- leachings 1-10	(mg g^{-1})	1.85	2.29	10.2	1.9	0.69	0.047
	(%)	36	73	78	9	47	39
- leachings 11-13^{1}	(mg g^{-1})	0.16	0.07	0.5	0.3	0.08	0.005
	(%)	4	2	4	2	6	4
- leachings 1-13	(mg g^{-1})	2.01	2.36	10.7	2.2	0.77	0.052
	(%)	40	75	82	11	53	43
Amount extracted by ultrasonic treatment	(mg g^{-1})	1.20	2.60	5.7	2.3	0.68	0.040
	(%)	24	83	44	11	47	33

1) One freeze/thaw treatment was made between leaching 10 and 11.

Table 3c. Initial amounts of plant nutrients in leaf litter of Alnus glutinosa and the loss of these nutrients at leaching. Figures are given both as relative amounts (%) and absolute amounts (mg g^{-1}) lost from 1000 mg dry weight of litter. All leachings were made at 24°C.

		N	P	K	Ca	Mg	Mn
Initial amount ($mg^{-}g^{-1}$)		21.0	0.56	3.90	27.9	3.33	0.67
Amount lost during:							
- leachings 1-10	(mg g^{-1})	0.22	0.35	3.07	6.8	2.03	0.34
	(%)	10	63	79	24	61	51
- leachings 11-13[1)]	(mg g^{-1})	0.06	0.02	0.04	0.3	0.08	0.02
	(%)	3	3	1	1	3	3
- leachings 1-13	(mg g^{-1})	0.28	0.37	3.11	7.1	2.11	0.36
	(%)	13	66	80	25	64	54
Amount extracted by ultrasonic treatment	(mg g^{-1})	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	(%)	-	-	-	-	-	-

1) One freeze/thaw treatment was made between leaching 10 and 11.

Table 3d. Initial amounts of plant nutrients in leaf litter of Sorbus aucuparia and the loss of these nutrients at leachings. Figures are given both as relative amounts (%) and absolute amounts (mg g^{-1}) lost from 1000 mg dry weight of litter. All leachings were made at 24°C.

		N	P	K	Ca	Mg	Mn
Initial amount (mg·g^{-1})		7.12	0.31	10.8	12.4	2.86	0.300
Amount lost during:							
- leachings 1-10	(mg g^{-1})	2.83	0.17	11.0	2.2	1.25	0.096
	(%)	40	55	102	18	44	32
- leachings 11-13[1]	(mg g^{-1})	0.18	0.04	0.3	0.1	0.06	0.006
	(%)	2	12	3	1	2	2
- leachings 1-13	(mg g^{-1})	3.01	0.21	11.3	2.3	1.31	0.102
	(%)	42	67	105	19	46	34
Amount extracted by ultrasonic treatment	(mg g^{-1})	0.87	0.17	11.6	2.8	1.31	0.084
	(%)	12	55	107	23	46	28

[1] One freeze/thaw treatment was made between leaching 10 and 11.

Table 3e. Initial amounts of plant nutrients in leaf litter of Populus tremula and the loss of these nutrients at leachings. Figures are given both as relative amounts (%) and absolute amounts (mg g^{-1}) lost from 1000 mg dry weight of litter. All leachings were made at 24°C.

		N	P	K	Ca	Mg	Mn
Initial amount (mg·g^{-1})		8.15	0.93	5.09	29.9	4.69	0.53
Amount lost during:							
- leachings 1-10	(mg g^{-1})	1.95	0.40	5.14	14.4	3.73	0.30
	(%)	24	43	101	48	80	57
- leachings 11-13[1)	(mg g^{-1})	0.84	0.04	0.05	0.2	0.04	0.01
	(%)	10	4	1	1	0	1
- leachings 1-13	(mg g^{-1})	2.79	0.44	5.19	14.6	3.77	0.31
	(%)	34	47	102	49	80	58
Amount extracted by ultrasonic treatment	(mg g^{-1})	1.06	0.57	6.92	12.1	3.83	0.29
	(%)	13	61	136	40	82	55

1) One freeze/thaw treatment was made between leaching 10 and 11.

Table 3f. Initial amounts of plant nutrients in leaf litter of Betula pubescens and the loss of these nutrients at leachings. Figures are given both as relative amounts (%) and absolute amounts (mg g^{-1}) lost from 1000 mg dry weight of litter. All leachings were made at 24^{0}C.

		N	P	K	Ca	Mg	Mn
Initial amount	(mg·g^{-1})	9.11	1.38	7.82	14.6	3.95	3.36
Amount lost during:							
- leachings 1-10	(mg g^{-1})	0.94	0.28	7.57	1.60	1.30	0.46
	(%)	10	20	97	11	33	14
- leachings 11-13 1)	(mg g^{-1})	0.21	0.06	0.98	0.44	0.32	0.12
	(%)	3	5	12	3	8	3
- leachings 1-13	(mg g^{-1})	1.15	0.34	8.55	2.04	1.62	0.58
	(%)	13	25	109	14	41	17
Amount extracted by ultrasonic treatment	(mg g^{-1})	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	(%)	-	-	-	-	-	-

1) One freeze/thaw treatment was made between leaching 10 and 11.

Table 3g. Initial amounts of plant nutrients in leaf litter of Salix caprea and the loss of these nutrients at leachings. Figures are given both as relative amounts (%) and absolute amounts (mg g^{-1}) lost from 1000 mg dry weight of litter. All leachings were made at 24°C.

		N	P	K	Ca	Mg	Mn
Initial amount	(mg·g^{-1})	9.41	0.49	11.9	28.5	3.37	0.120
Amount lost during:							
- leachings 1-10	(mg g^{-1})	1.97	0.12	13.0	9.5	1.75	0.054
	(%)	21	24	109	33	52	45
- leachings 11-13[1]	(mg g^{-1})	0.37	0.00	0.1	0.3	0.05	0.002
	(%)	4	0	1	1	1	2
- leachings 1-13	(mg g^{-1})	2.34	0.12	13.1	9.8	1.80	0.056
	(%)	25	24	110	34	53	47
Amount extracted by ultrasonic treatment	(mg g^{-1})	0.84	0.20	11.0	12.9	2.24	0.059
	(%)	9	41	92	45	66	49

1) One freeze/thaw treatment was made between leaching 10 and 11.

Table 3h. Initial amounts of plant nutrients in leaf litter of Pinus silvestris and the loss of these nutrients at leachings. Figures are given both as relative amounts (%) and absolute amounts (mg g^{-1}) lost from 1000 mg dry weight of litter. All leachings were made at 24°C.

		N	P	K	Ca	Mg	Mn
Initial amount (mg·g^{-1})		3.61	0.27	0.95	7.50	0.35	1.74
Amount lost during:							
- leachings 1-10	(mg g^{-1})	0.48	0.014	0.08	0.16	0.01	0.01
	(%)	13	5	8	2	3	1
- leachings 11-13[1]	(mg g^{-1})	0.07	0.002	0.12	0.03	0.02	0.02
	(%)	2	1	13	1	6	1
- leachings 1-13	(mg g^{-1})	0.55	0.016	0.20	0.19	0.03	0.03
	(%)	15	6	21	3	9	2
Amount extracted by ultrasonic treatment	(mg g^{-1})	0.57	0.114	0.95	0.88	0.26	0.95
	(%)	16	42	100	12	74	55

1) One freeze/thaw treatment was made between leaching 10 and 11.

Table 3i. Initial amounts of plant nutrients in leaf litter of Pinus silvestris (fertilized) and the loss of these nutrients at leachings. Figures are given both as relative amounts (%) and absolute amounts (mg g^{-1}) lost from 1000 mg dry weight of litter. All leachings were made at 24°C.

		N	P	K	Ca	Mg	Mn
Initial amount (mg·g^{-1})		4.85	0.190	0.98	4.90	0.590	1.01
Amount lost during:							
- leachings 1-10	(mg g^{-1})	0.30	0.005	0.46	0.07	0.038	0.03
	(%)	6	3	47	1	6	3
- leachings 11-13[1)]	(mg g^{-1})	0.12	0.012	0.20	0.04	0.026	0.03
	(%)	3	6	20	1	5	3
- leachings 1-13	(mg g^{-1})	0.42	0.017	0.66	0.11	0.064	0.06
	(%)	9	9	67	2	11	6
Amount extracted by ultrasonic treatment	(mg g^{-1})	1.14	0.055	1.12	0.57	0.333	0.48
	(%)	24	29	114	12	56	48

1) One freeze/thaw treatment was made between leaching 10 and 11.

Table 4. The coefficient of determination (r^2) for the linear relationship between initial concentration in the litters and the accumulated loss of the respective elements after 10 leachings in water. The loss rates were expressed as mg g^{-1} dw (absolute loss) and as per cent of original amount. N=9 (all litter types) and 7 (broad-leaf litters). Significance levels: * = p<0.05, ** = p<0.01 and *** = p<0.001).

	Elements:					
	N	P	K	Ca	Mg	Mn
Absolute loss:						
- all litter types	-0.05	0.86***	0.91***	0.71**	0.68**	0.33
- broad-leaf litters	0.60*	0.84**	0.82**	0.71*	0.40	0.66*
Percent loss: (leachability)						
- all litter types	0.07	0.39	0.34	0.73**	0.34	0.42
- broad-leaf litters	0.42	0.24	0.04	0.64*	0.00	0.57

Table 5. Amounts of phenolic/polyphenolic substances lost from the different leaf litter types by leaching. Figures are expressed as mg phenol per 1000 mg dry weight of the litter. All leachings were made at 24°C.

	Phenolic substances (mg phenol · mg^{-1}dw)		
Species	leachings 1-10	leachings 11-13[1)]	leachings 1-13
Fraxinus excelsior	4.54	0.21	4.75
Acer platanoides	12.39	1.36	13.75
Alnus glutinosa	6.52	1.34	7.86
Sorbus aucuparia	1.60	0.30	1.90
Populus tremula	4.79	0.20	4.99
Betula pubescens	0.41	0.11	0.52
Salix caprea	6.03	0.53	6.56
Pinus silvestris	0.01	0.16	0.17
Pinus silvestris (fertilized)	0.06	0.11	0.17

1) One freeze/thaw treatment was made between leachings 10 and 11.

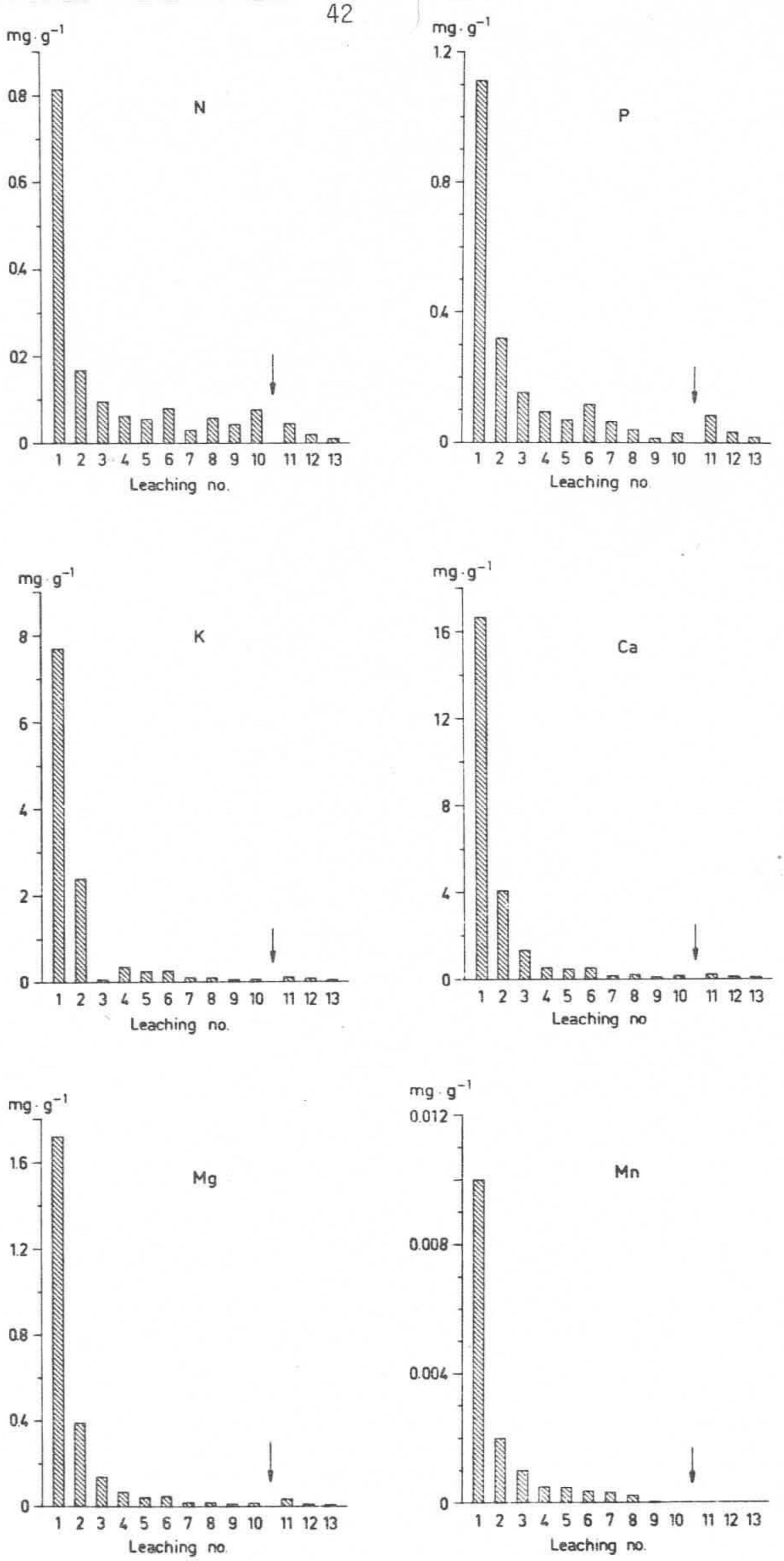


Figure 1a. Amounts of N, P, K, Ca, Mg and Mn lost from Fraxinus excelsior leaf litter during 13 consecutive leachings. The arrows indicate the position of a freeze/thaw treatment. All leachings were made in water at 24°C.

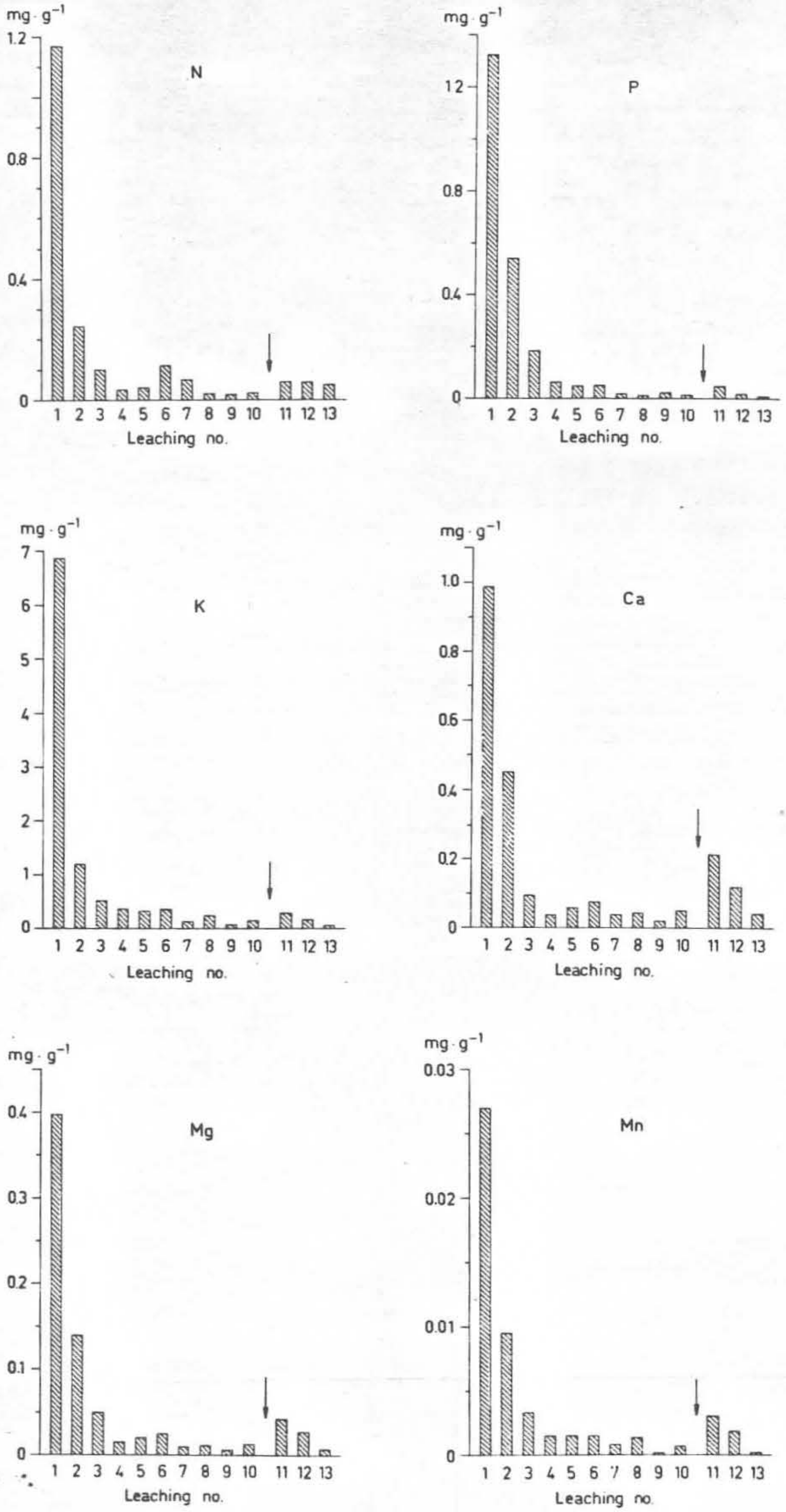


Figure 1b. Amounts of N, P, K, Ca, Mg and Mn lost from Acer platanoides leaf litter during 13 consecutive leachings. The arrows indicate the position of a freeze/thaw treatment. All leachings were made in water at 24^{o}C.

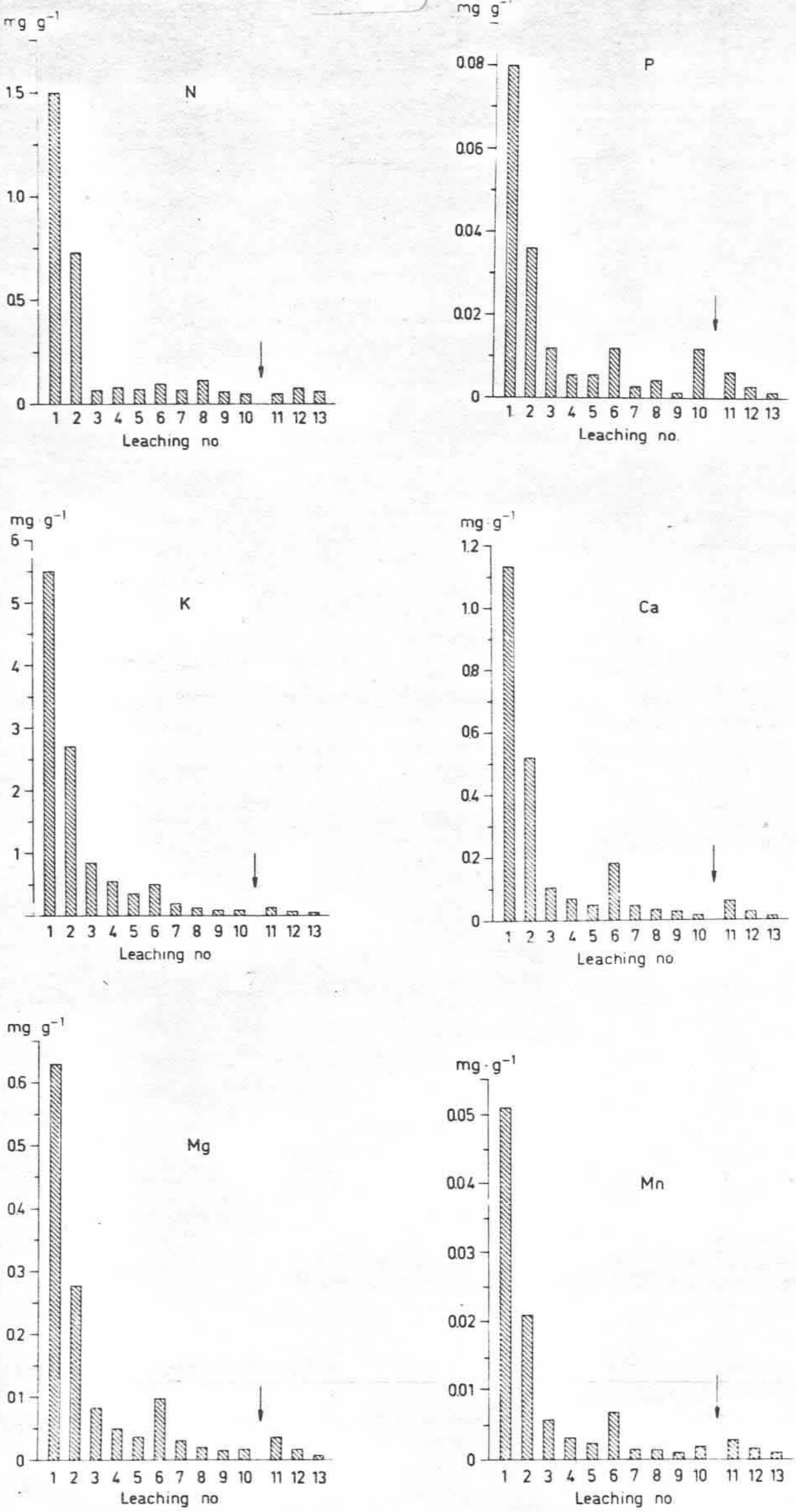


Figure 1c. Amounts of N, P, K, Ca, Mg and Mn lost from Alnus glutinosa leaf litter during 13 consecutive leachings. The arrows indicate the position of a freeze/thaw treatment. All leachings were made in water at 24°C.

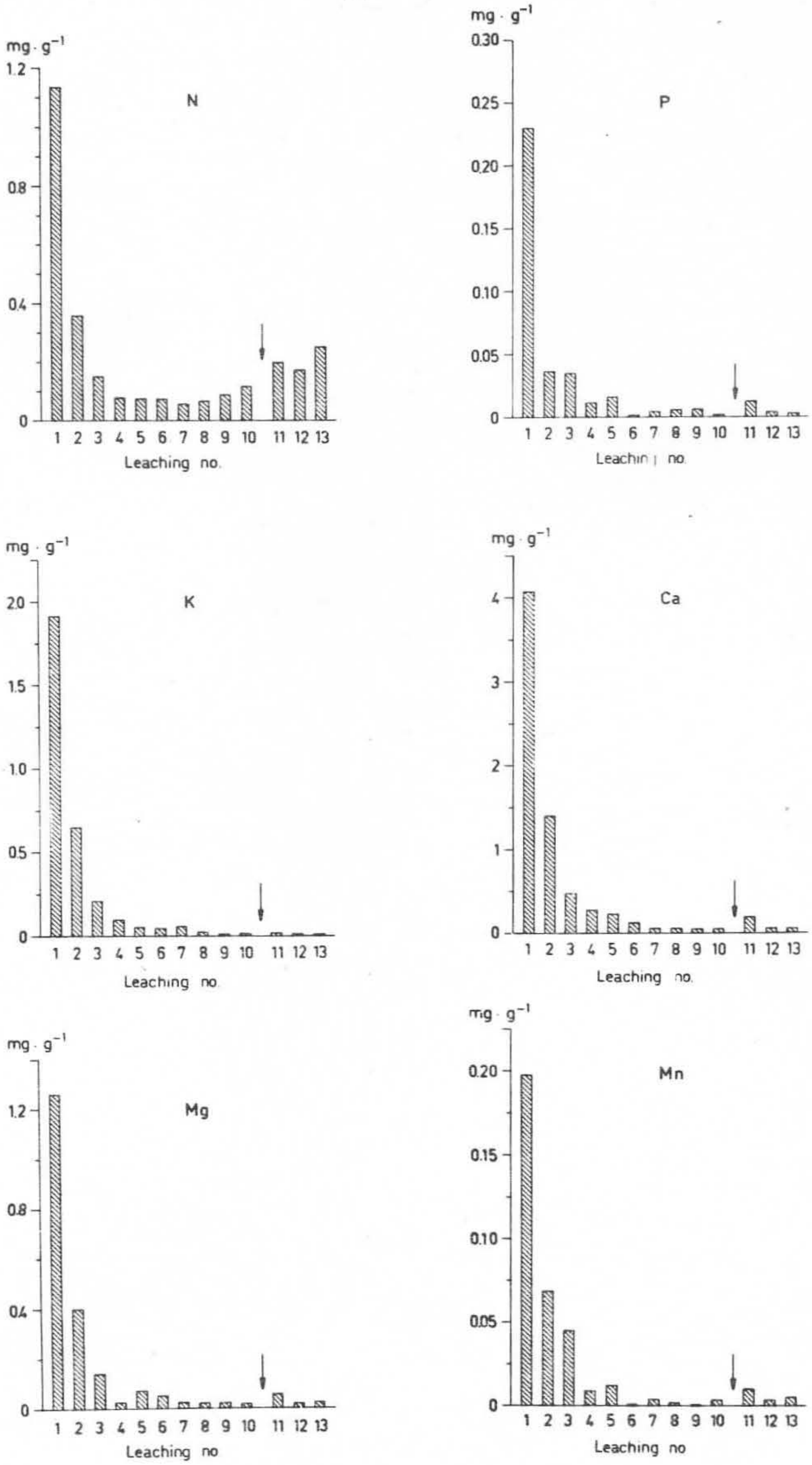


Figure 1d. Amounts of N, P, K, Ca, Mg and Mn lost from Sorbus aucuparia leaf litter during 13 consecutive leachings. The arrows indicate the position of a freeze/thaw treatment. All leachings were made in water at 24°C.

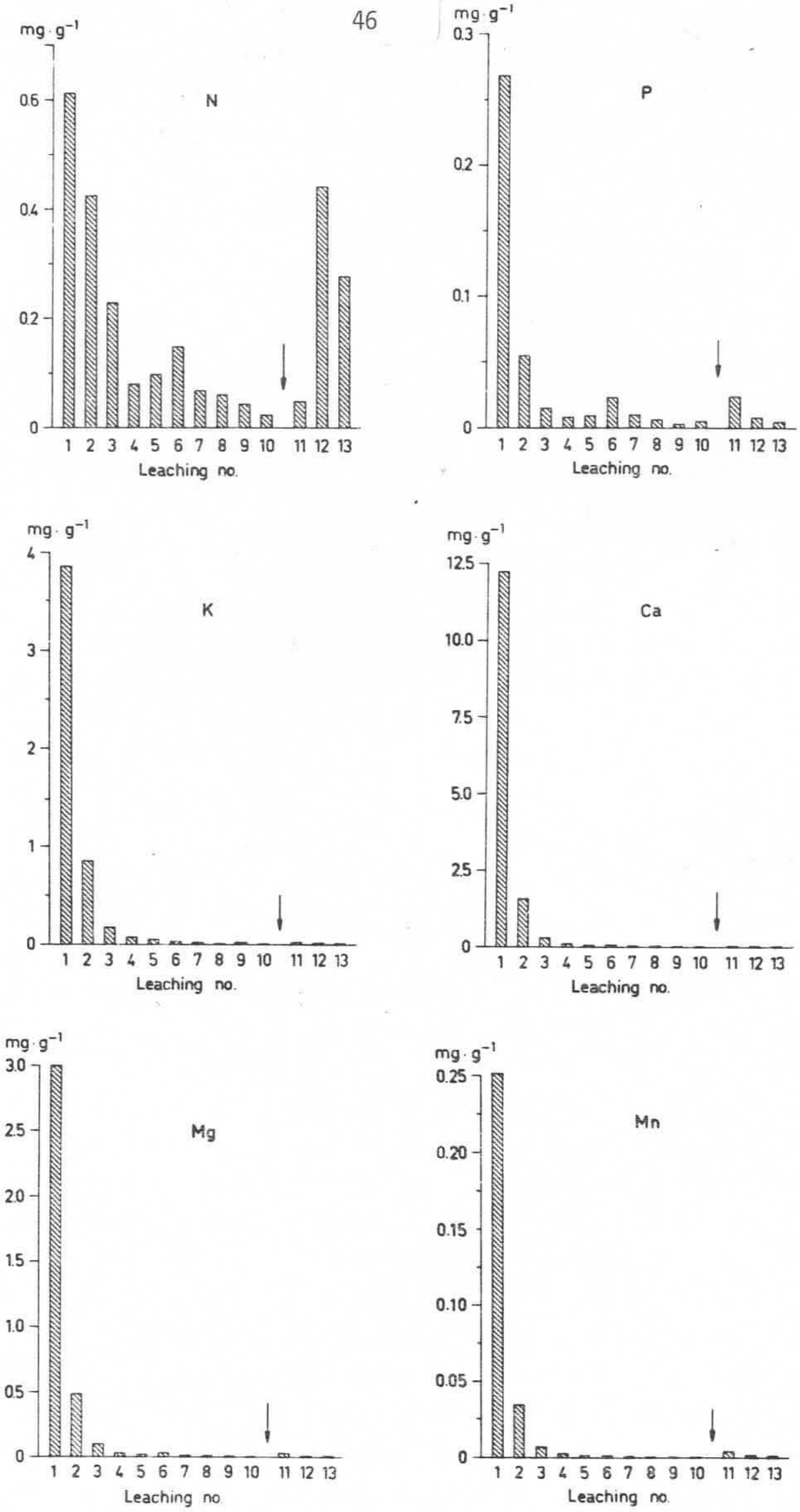


Figure 1e. Amounts of N, P, K, Ca, Mg and Mn lost from Populus tremula leaf litter during 13 consecutive leachings. The arrows indicate the position of a freeze/thaw treatment. All leachings were made in water at 24°C.

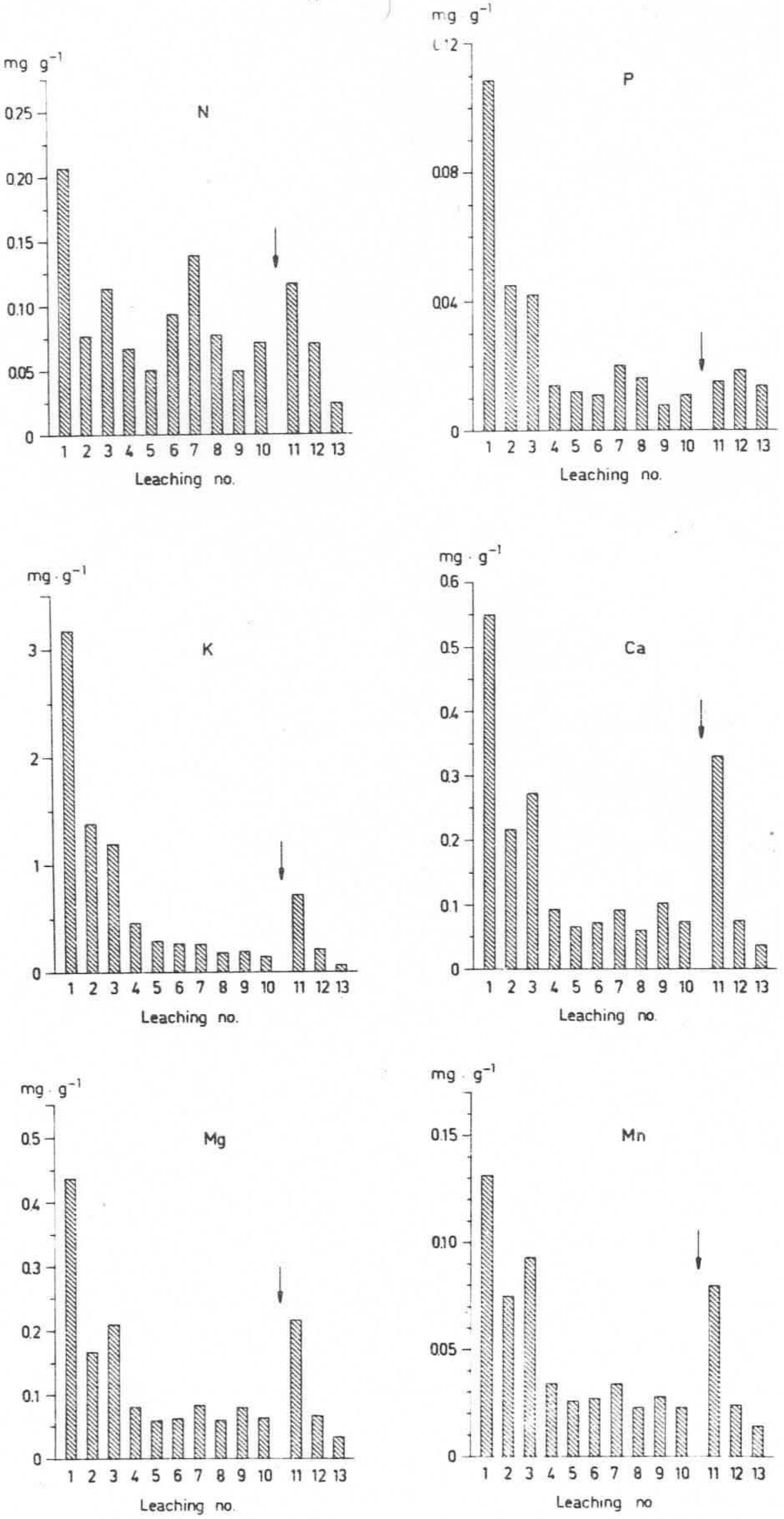


Figure 1f. Amounts of N, P, K, Ca, Mg and Mn lost from Betula pubescens leaf litter during 13 consecutive leachings. The arrows indicate the position of a freeze/thaw treatment. All leachings were made in water at 24°C.

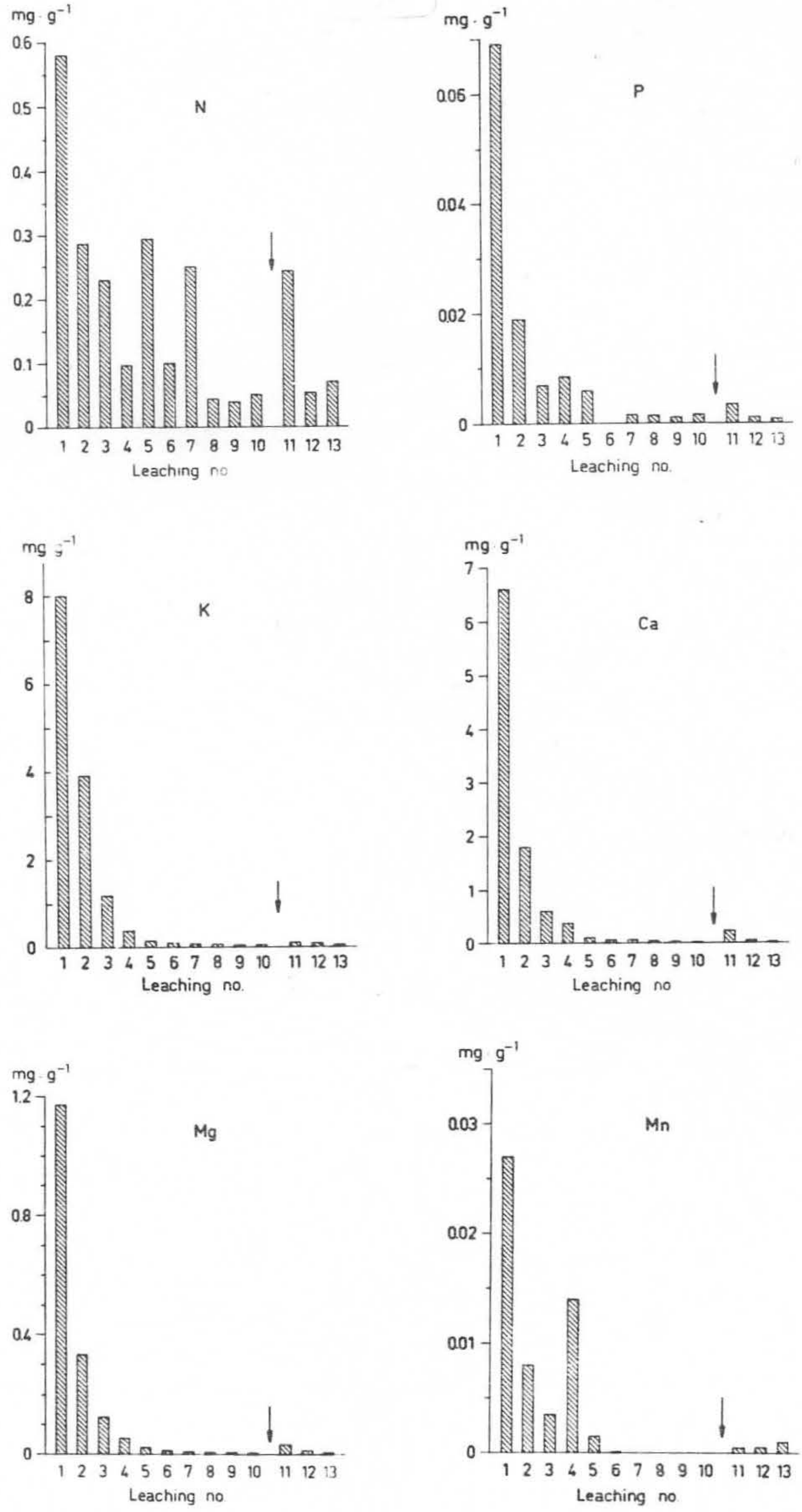


Figure 1g. Amounts of N, P, K, Ca, Mg and Mn lost from Salix caprea leaf litter during 13 consecutive leachings. The arrows indicate the position of a freeze/thaw treatment. All leachings were made in water at 24°C.

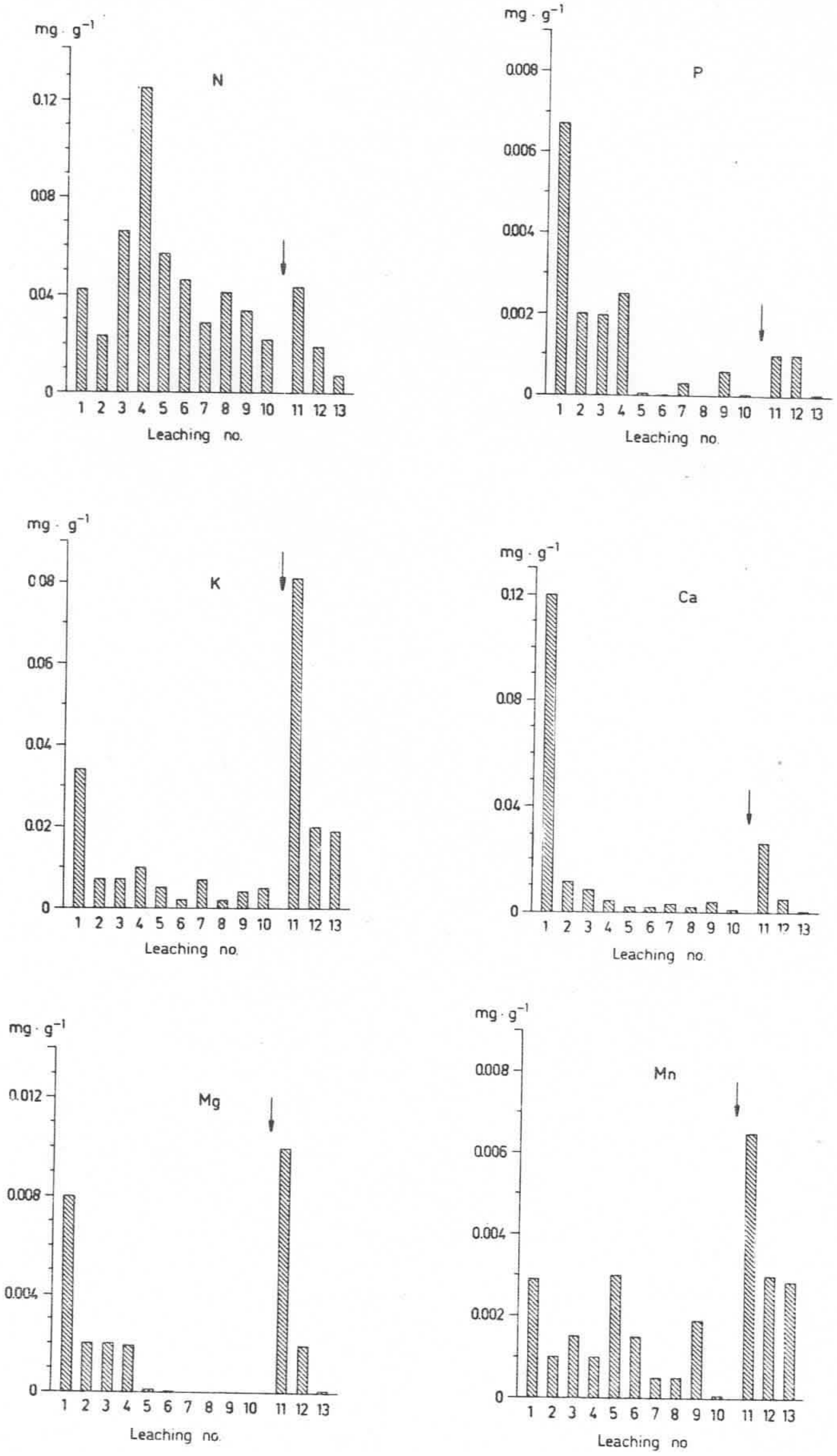


Figure 1h. Amounts of N, P, K, Ca, Mg and Mn lost from Scots pine needle litter during 13 consecutive leachings. The arrows indicate the position of a freeze/thaw treatment. All leachings were made in water at 24°C.

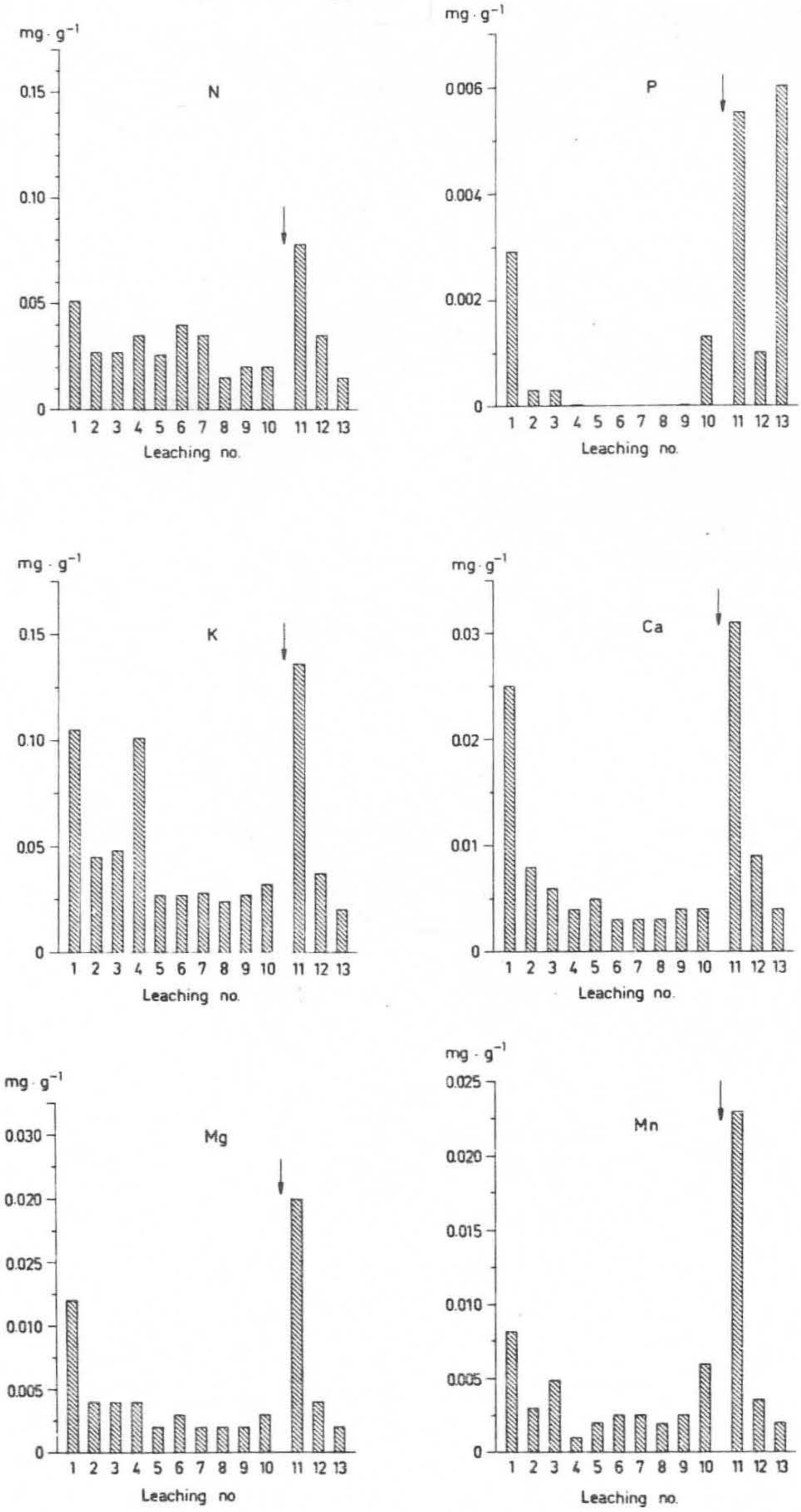


Figure 1i. Amounts of N, P, K, Ca, Mg and Mn lost from Scots pine needle litter (fertilized trees) during 13 consecutive leachings. The arrows indicate the position of a freeze/thaw treatment. All leachings were made in water at 24^{0}C.

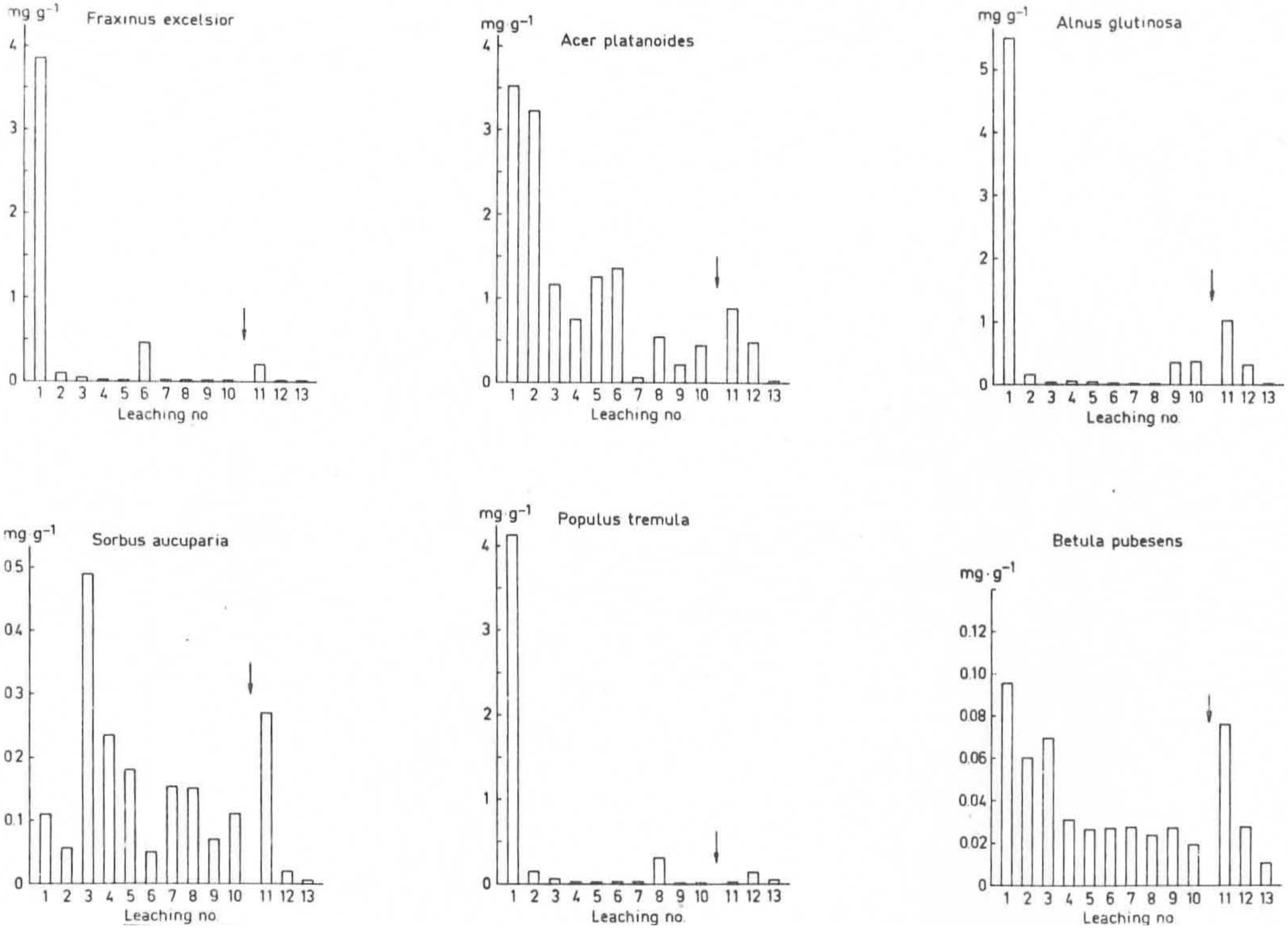
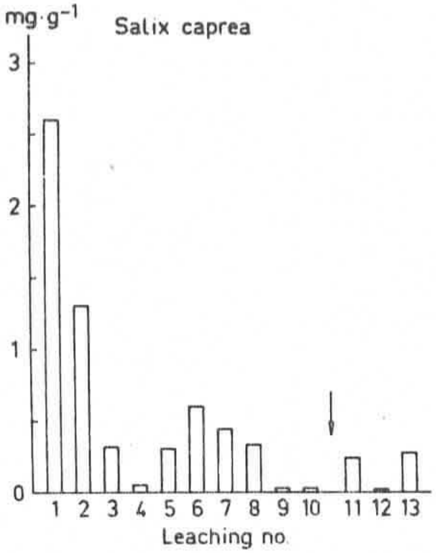
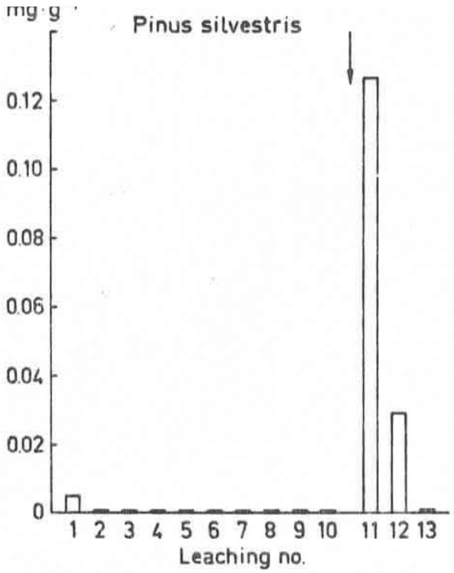
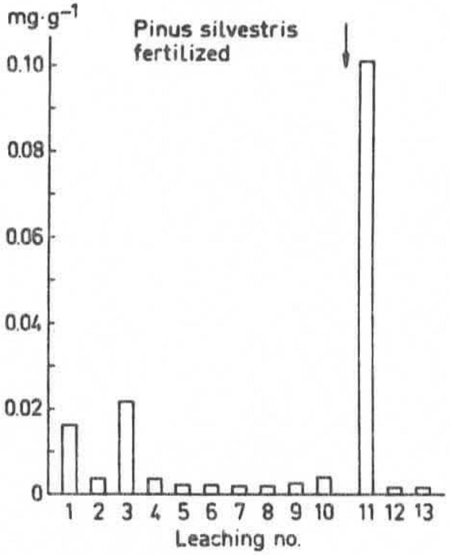


Figure 2a-i. Amounts of polyphenols lost from the different leaf litter types during 13 consecutive leachings. The arrows indicate the position of a freeze-thaw treatment. All leachings were made in water at 24°C.


mg·g⁻¹
Salix caprea
3
2
1
0
1 2 3 4 5 6 7 8 9 10 11 12 13
Leaching no.


mg·g⁻¹
Pinus silvestris
0.12
0.10
0.08
0.06
0.04
0.02
0
1 2 3 4 5 6 7 8 9 10 11 12 13
Leaching no.


mg·g⁻¹
Pinus silvestris
fertilized
0.10
0.08
0.06
0.04
0.02
0
1 2 3 4 5 6 7 8 9 10 11 12 13
Leaching no.

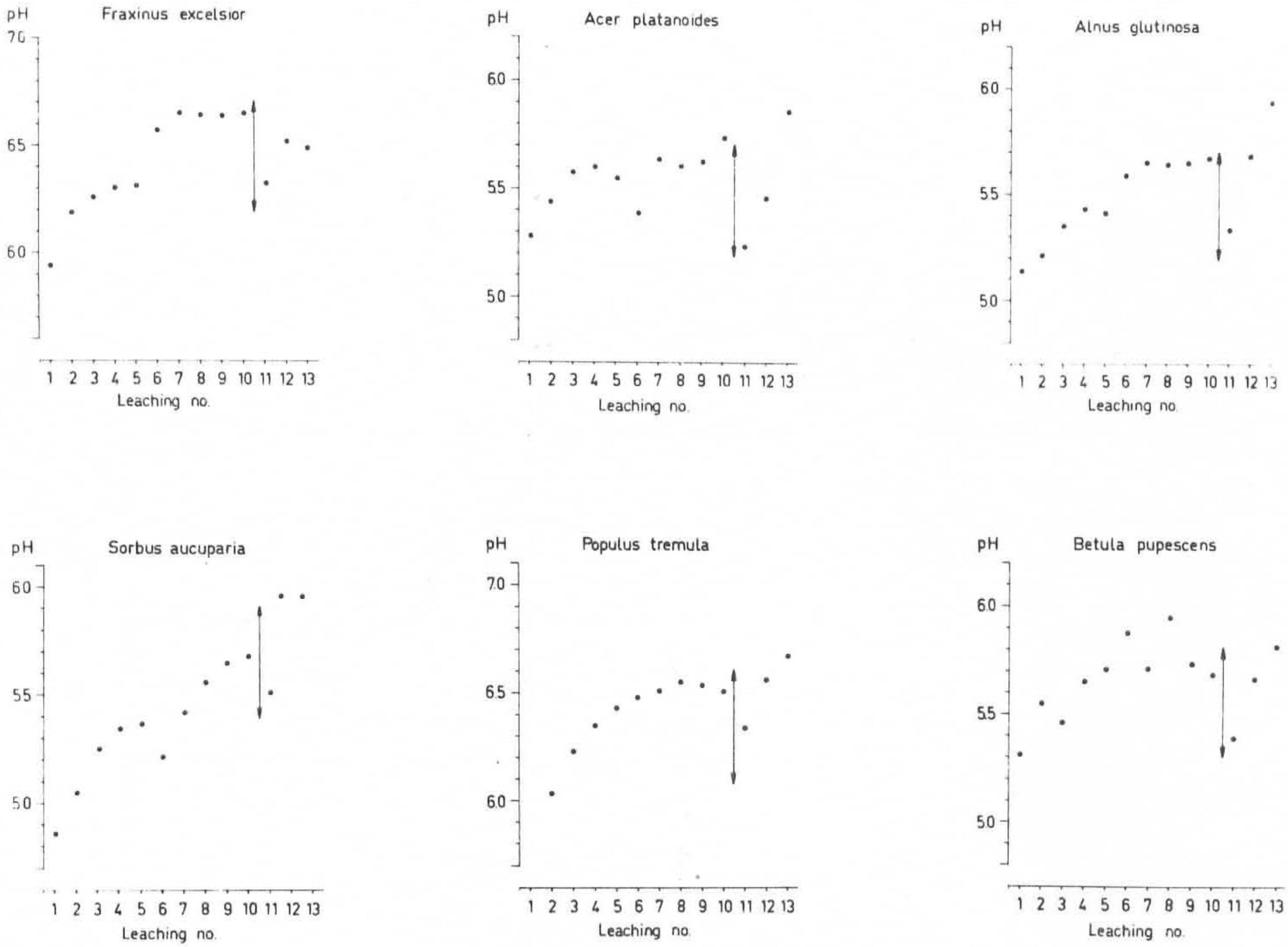
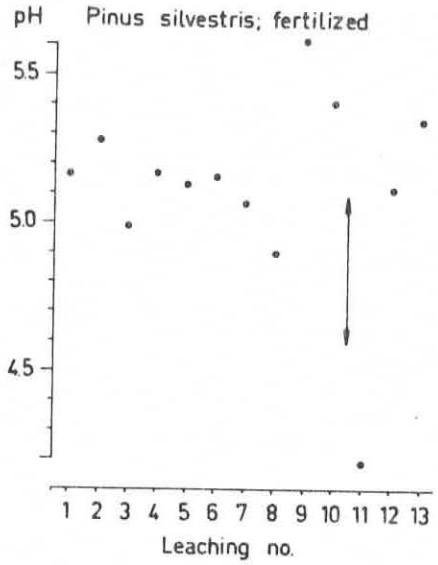
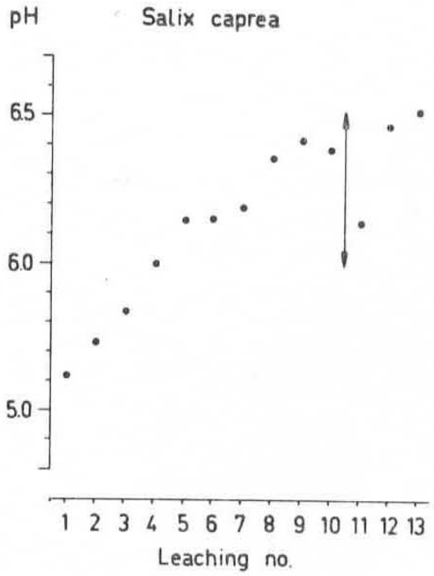
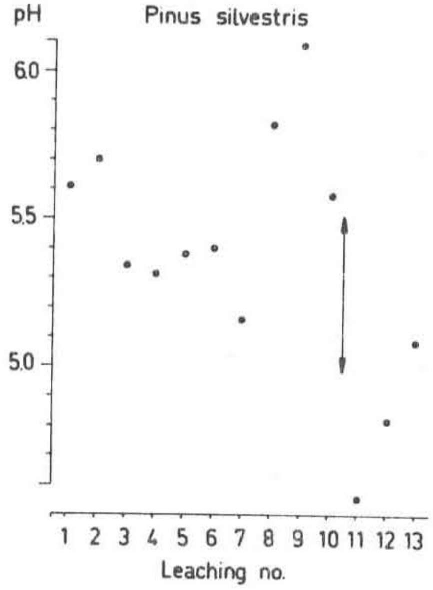


Figure 3a-i. pH of leachates form the different litter types. The arrows indicate the position of a freeze/thaw treatment.


pH
Pinus silvestris; fertilized
5.5
5.0
4.5
1 2 3 4 5 6 7 8 9 10 11 12 13
Leaching no.


pH
Salix caprea
6.5
6.0
5.0
1 2 3 4 5 6 7 8 9 10 11 12 13
Leaching no.


pH
Pinus silvestris
6.0
5.5
5.0
1 2 3 4 5 6 7 8 9 10 11 12 13
Leaching no.

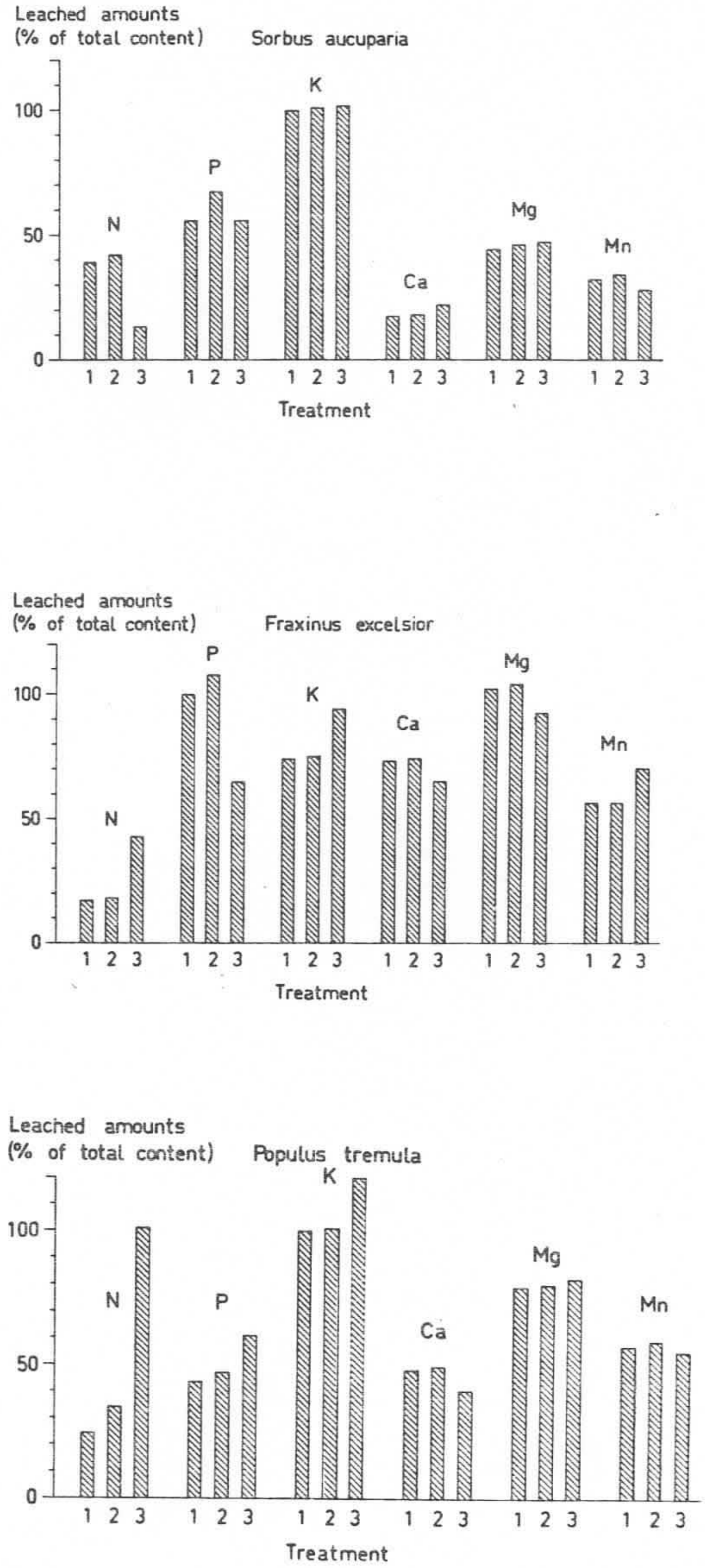
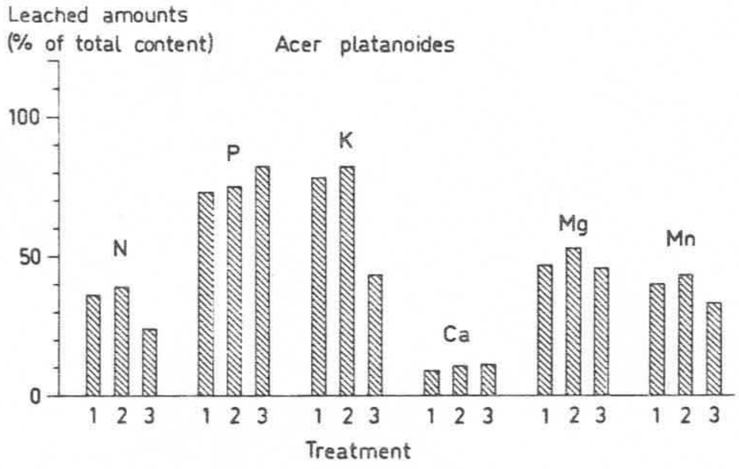
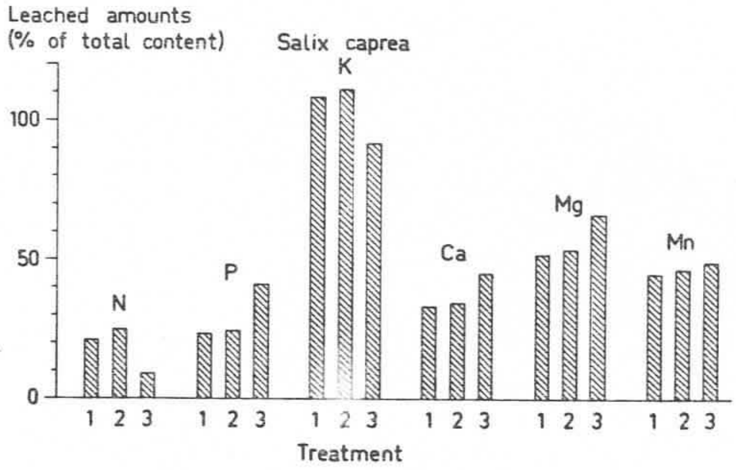
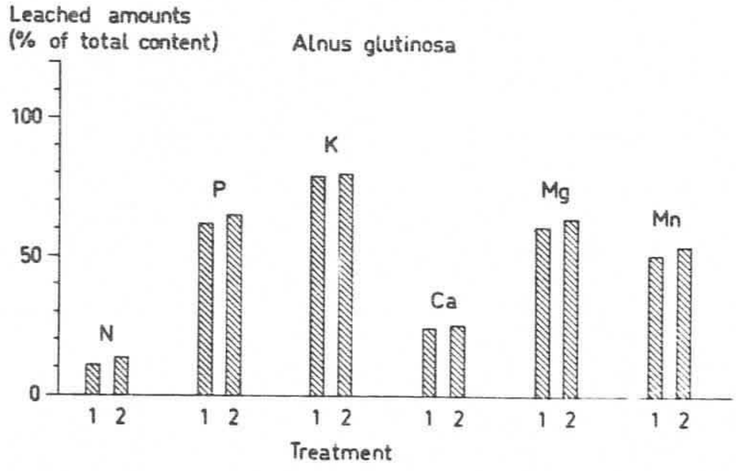
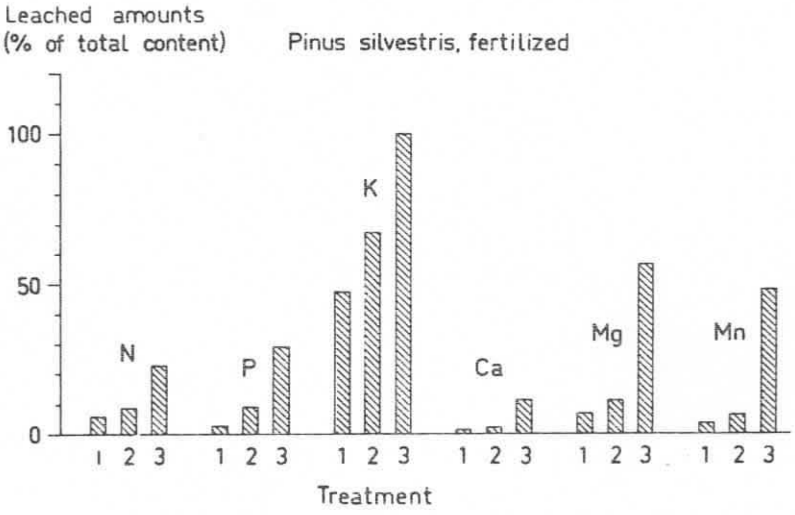


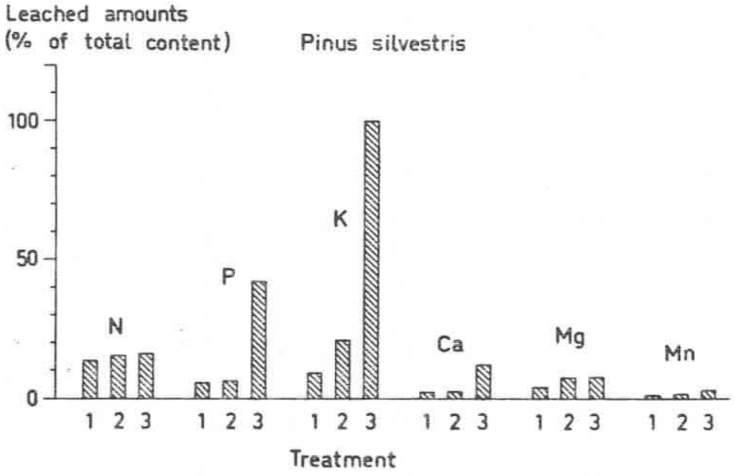
Figure 4a-i. The loss of N, P, K, Ca, Mg and Mn in per cent of the total amount of the respective element in the different litter types during various leaching treatments. 1 = leaching 1-10, 2 = leaching 11-13, 3 = one leaching after ultra-sonic treatment of the litter.

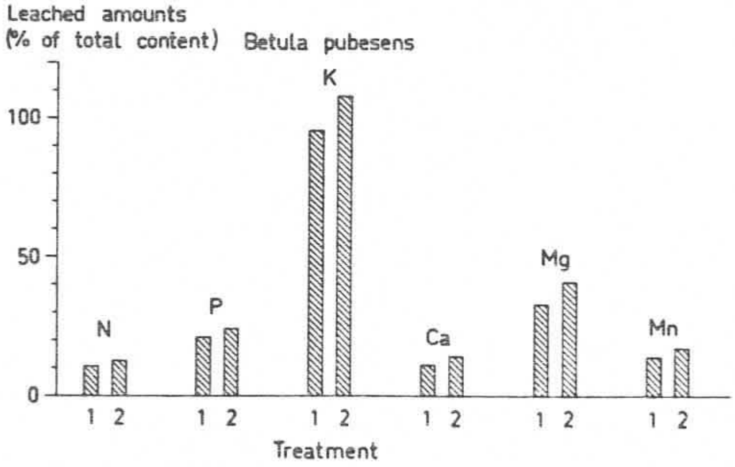

Leached amounts
(% of total content)
Acer platanoides
100
50
0
N
P
K
Ca
Mg
Mn
1 2 3
Treatment


Leached amounts
(% of total content)
Salix caprea
100
50
0
N
P
K
Ca
Mg
Mn
1 2 3
Treatment


Leached amounts
(% of total content)
Alnus glutinosa
100
50
0
N
P
K
Ca
Mg
Mn
1 2
Treatment


Leached amounts
(% of total content)
Pinus silvestris, fertilized
100
50
0
N
P
K
Ca
Mg
Mn
1 2 3
1 2 3
1 2 3
1 2 3
1 2 3
1 2 3
Treatment


Leached amounts
(% of total content)
Pinus silvestris
100
50
0
N
P
K
Ca
Mg
Mn
1 2 3
1 2 3
1 2 3
1 2 3
1 2 3
1 2 3
Treatment


Leached amounts
(% of total content)
Betula pubesens
100
50
0
N
P
K
Ca
Mg
Mn
1 2
1 2
1 2
1 2
1 2
1 2
Treatment